SILICA ROD BASED OPTICAL FIBRE SENSOR FOR HIGH REFRACTIVE INDEX SENSING APPLICATION IN AGEING POWER TRANSFORMER OIL

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DEDICATION

Specially dedicated to:

My dear husband, Muhamad Zulfarhan bin Muhamad Zaimi, and my sons, Umar and Harith. I am truly grateful for your willingness to share with me the struggles that I have endured throughout this journey.

My beloved mother, Jumirah binti Misran, my siblings, and my family-in-law, I am indebted for all the kindness you all have showered upon me.

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ABSTRACT

Power transformer is one of the most essential components in power transmission and distribution systems. A thorough inspection of the condition of a power transformer is critical to avert malfunctions. An essential part of this inspection includes degradation control of the transformer oil. In fact, studies have incorporated optical fibre sensors (OFSs) for transformer oil degradation detection owing to the distinct advantages of OFS over conventional methods. Despite the diversity of techniques which have been employed for the developed OFSs, they pose problems of complicated fabrication and cross-sensitivity to temperature. As such, this study reports the original research work on the development of high refractive index (RI) fibre sensors based on silica rod (SR) structure to address the aforementioned problems. This study details the conceptual sensor design, the fabrication, the experimentation, and the application to transformer oil degradation detection. Related mathematical models of the sensor architectures, such as principles of leaky mode interference (LMI) and multimode interference (MMI), were explored to comprehend sensor behaviour. The sensors were numerically analysed using BeamPROP software to determine their functions from field distribution and sensor spectra. Systematic procedures for fabrication and experimentation of the sensor were developed to ensure high repeatability. Notably, four sensor designs are proposed in this study. Design 1 signifies RI sensing based on wavelength shift and spectrum power level change. The use of SR as a sensing element induced the spectrum power level change due to the LMI at the SR section. Meanwhile, spectrum wavelength shift was induced because the input of MMI in MMF was substantially influenced by its surrounding high RI. The sensor responded to the surrounding RI by the changes of dip wavelength and output power level with maximum sensitivity of 38.65 nm/RIU and 63.15 dBm/RIU, respectively. Design 2 is proposed to simultaneously measure high RI and temperature by monitoring the respective output power level and wavelength shift of the single dip transmission spectrum of the sensor. The experimental results revealed that the sensor had RI sensitivity of 108.07 dBm/RIU and temperature sensitivity of 9.31 pm/^{o}C. Design 3 deployed a SR with larger diameter exceeding the MMF core diameter to increase the leakage loss of high-order leaky modes to the surrounding. By monitoring the output power of the interference dip, this sensor achieved 5-fold greater sensitivity than Design 1, which was up to -293.53 dBm/RIU. Design 4 refers to a full intensity-based RI sensor that completely depends on the LMI at the SR section. The measurement of high RI was executed by monitoring the spectrum power level change caused by LMI. The sensitivity of this sensor was 93.82 dBm/RIU. Design 4 sensor was selected and applied in power transformer applications to detect transformer oil degradation due to its compact structure, easy interrogation scheme, and resistance to temperature variations. The findings revealed that the sensor was capable of sensing the variations of oil that belonged to the good and fair regions in accordance to ASTM D1500 colour scale. This scenario highlights the great potential of the sensor for remote in-situ detection of transformer oil degradation.

ABSTRAK

Pengubah kuasa adalah salah satu komponen yang paling penting dalam sistem penghantaran dan pengedaran kuasa. Pemeriksaan menyeluruh keadaan pengubah kuasa adalah penting untuk mengelak kerosakan pengubah kuasa. Bahagian penting dalam pemeriksaan ini termasuk kawalan kemerosotan minyak pengubah. Kajian telah dilakukan untuk menggabungkan penderia gentian optik (OFS) untuk pengesanan kemerosotan minyak pengubah kerana kelebihan tersendiri OFS berbanding kaedah konvensional. Walaupun terdapat pelbagai teknik berbeza telah digunakan untuk OFS yang dibangunkan, mereka mempunyai masalah fabrikasi yang rumit dan kepekaan silang terhadap suhu. Oleh itu, kajian ini melaporkan penyelidikan asal mengenai pembangunan penderia gentian indeks biasan (RI) tinggi berdasarkan struktur rod silika (SR) untuk menangani masalah yang disebutkan di atas. Kerja penyelidikan ini melibatkan rekabentuk konsep penderia, fabrikasi, eksperimen, dan aplikasi untuk pengesanan kemerosotan minyak pengubah. Model matematik berkaitan seni bina penderia seperti prinsip interferens antara mod bocor (LMI) dan interferens antara pelbagai mod (MMI) telah diterokai untuk memahami tingkah laku penderia. Penderia dianalisis secara berangka menggunakan perisian BeamPROP untuk memahami fungsi mereka dari taburan medan dan spektrum penderia. Prosedur sistematik untuk fabrikasi dan eksperimen penderia telah dibangunkan untuk memastikan kebolehulangan yang tinggi. Secara umum, empat rekabentuk penderia telah dicadang dalam kajian ini. Rekabentuk 1 merujuk kepada penderiaan RI berdasarkan peralihan panjang gelombang dan perubahan aras kuasa spektrum. Penggunaan SR sebagai elemen penderiaan menyebabkan perubahan aras kuasa spektrum yang disebabkan oleh LMI di bahagian SR. Sementara itu, peralihan panjang gelombang spektrum disebabkan oleh input MMI dalam MMF ketara dipengaruhi oleh RI sekitar yang tinggi. Penderia bertindak balas terhadap RI di sekitarnya dengan perubahan panjang gelombang dan aras kuasa keluaran dengan kepekaan maksimum, masing-masing sebanyak 38.65 nm/RIU dan 63.15 dBm/RIU. Rekabentuk 2 penderia dicadang untuk mengukur RI dan suhu yang tinggi secara serentak dengan memantau aras kuasa keluaran dan peralihan panjang gelombang yang berkenaan pada spektrum transmisi dip tunggal penderia. Hasil eksperimen menunjukkan bahawa penderia ini mempunyai kepekaan RI sebanyak 108.07 dBm/RIU, manakala kepekaan suhu adalah 9.31 pm/^{o}C. Penderia rekabentuk 3 menggunakan SR yang lebih besar dengan diameter melebihi diameter teras MMF untuk meningkatkan pendedahan mod bocor tertib tinggi ke sekitarnya. Dengan memantau kuasa keluaran dip interferens, penderia ini mencapai 5 kali ganda kepekaan RI berbanding rekabentuk 1 iaitu sehingga -293.53 dBm/RIU. Penderia rekabentuk 4 adalah penderia RI berasaskan intensiti penuh yang sepenuhnya bergantung kepada LMI di bahagian SR. Pengukuran RI tinggi direalisasikan dengan memantau perubahan aras kuasa spektrum yang disebabkan oleh LMI. Penderia ini mencapai kepekaan sehingga 93.82 dBm/RIU. Rekabentuk 4 telah dipilih dan digunakan dalam aplikasi pengubah kuasa untuk mengesan kemerosotan minyak pengubah disebabkan struktur yang kecil, skim soal siasat yang mudah, dan ketahanan terhadap variasi suhu. Hasil kajian menunjukkan bahawa penderia tersebut mampu menderia variasi minyak yang tergolong dalam kawasan yang baik dan sederhana mengikut skala warna ASTM D1500. Senario ini menyerlahkan potensi besar penderia untuk pengesanan in-situ mudah alih kemerosotan minyak pengubah.

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LIST OF ABBREVIATIONS

2D - Two-dimension
3D - Three-dimension
ASE - Amplified Spontaneous Emission
ASTM - American Society for Testing and Materials
CH_4 - Methane
C_2H_3 - Acetylene
C_2H_4 - Ethylene
C_2H_6 - Ethane
CO - Carbon monoxide
CO_2 - Carbon dioxide
DGA - Dissolved gas analysis
EMI - Electromagnetic interference
ER - Extinction ratio
FBG - Fibre Bragg grating
FPI - Fabry-Perot interferometry
GLG - Guided-mode-leaky-mode-guided-mode
GMI - Guided Mode Interference
H_2 - Hydrogen
HF - Hydrofluoric
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronic Engineers
IFT - Interfacial tension
IoT - Internet of Things
IR - Industrial Revolution
ITO - Indium-tin-oxide
KOH - Potassium hydroxide
LED - Light emitting diode
LMF - Leaky mode fibre
LMI - Leaky mode interference
LMR - Lossy mode resonance

LP - Linear polarization
LPG - Long-period grating
MMF - Multimode fibre
MMI - Multimode interference
MZI - Mach-Zender interferometry
N_2 - Nitrogen
NCF - No core fibre
O_2 - Oxygen
OFS - Optical fibre sensors
OSA - Optical spectrum analyser
POF - Plastic optical fibre
RFI - Radio frequency interference
RI - Refractive index
RIU - Refractive index unit
SFBG - Slanted fibre Bragg grating
SMF - Single mode fibre
SMS - Single-mode-multimode-single-mode
SSMS - Single-mode-silica rod-multimode-single-mode (Design 1)
SSRS - Single-mode-silica rod-single-mode
SSRMS - Single-mode-silica rod-multimode-single-mode (Design 3)
SnO_2 - Tin-dioxide
SR - Silica rod
TAN - Total acid number
TOC - Thermo-optic coefficient
US - United States

LIST OF SYMBOLS

α_m - Attenuation constant of the m^{th} leaky mode
λ_{FBG} - Centre wavelength of FBG
η_m - Coupling coefficient m^{th} mode
D - Diameter
n_{eff} - Effective refractive index
E_{in} - Electrical field of fundamental mode in input SMF
E_{out} - Electrical field of fundamental mode in output SMF
E_m - Electrical field of m^{th} leaky mode
c_m - Excitation coefficient of m^{th} mode or leaky mode
$\Delta\lambda_{FBG}$ - FBG wavelength shift dip
Λ - Grating period
N - Integer
M - Mode number
m - Mode order m
n - Mode order n
L_{MMF} - Multimode fibre length
V - Normalized frequency
T_{out} - Output intensity
$\Delta\emptyset_{mn}$ - Phase difference between m^{th} and n^{th} modes
β - Propagation constant
β_m - Propagation constant of m^{th} mode or leaky mode
β_n - Propagation constant n^{th} mode
a - Radius of MMF core
n_{cl} - Refractive index of MMF cladding
n_{co} - Refractive index of MMF core
D_{SR} - Silica rod diameter
L_{SR} - Silica rod length
L_{SMF} - Single-mode fibre length
ΔT - Temperature change
α - Thermal expansion coefficient

ξ - Thermo-optic coefficient

λ - Wavelength

λ_c - Wavelength of destructive interference

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Power Transformer

Transformers that are applied in electrical transmission system to step-up and step-down voltage levels in order to minimise power loss on transmission lines are called power transformers. Power transformers are the most expensive and essential pieces of equipment used in high-voltage power grid and play a critical role in power system [1-3]. In any event that a failure occurs in service, the impact can be far reaching. The Northeast Blackout of 2003 (in August 14th), which affected several eastern cities in the US and Canada, demonstrated how power outages have significant social and economic consequences [4]. Although such severe power outages are uncommon, electrical utility businesses often suffer outages of a smaller magnitude that are not only inconvenient to both companies and their customers, but also can result in revenue loss. Besides, failure of power transformers may result in costly repairs and potentially serious injury or fatality [5, 6]. Hence, power transformers are subject to regular inspection and maintenance procedures to ensure their smooth and continuous operation, also to prolong the life of these valuable assets [7]. The maintenance activities, including condition monitoring and diagnosis of power transformers, have many great benefits as listed in the following [8, 9].

1. It can promptly recognise faults, thus an early fault diagnosis can be provided to avoid critical conditions and extremity of any damage incurred.
2. Quality of supply and safety of persons are guaranteed by limiting the probability of destructive failure.
3. It reduces equipment repairing activities and costs.
4. The remaining useful life of a power transformer can be extended.

An insulation system using both liquid and paper is often used for power transformers. Numerous maintenance operations are meant to prolong the life of a power transformer, such as examining the physical state of transformer bushings, tanks, and gaskets, while most experts believe that the most essential maintenance process is monitoring the equipment insulation. The typical life of a power transformer ranges from 20 to 25 years based on various standards organisations (e.g., Institute of Electrical and Electronic Engineers (IEEE)) and the lifespan is generally linked to the quality of transformer insulation [10, 11].

Paper insulation made of cellulose, namely Kraft-paper, has typically been used to insulate transformer conductors and may also be applied to insulate high voltage cables. A good insulating paper has excellent dielectric properties, high thermal rating, and minimal moisture absorption. The state of the paper will deteriorate throughout the lifespan of a transformer as a result of exposure to high temperatures, moisture, oxygen, and a variety of other pollutants present in the insulating system. In many situations, paper offers insulation in tandem with oil, in which case, the quality of both oil and paper impacts the lifespan of the equipment.

Oil is utilised in electrical equipment not just for its capacity to offer excellent electrical insulation, but also for its great temperature stability. The main function of oil is to absorb heat generated by the power transformer winding and core, apart from transmitting heat to radiator or tank surfaces of the power transformer aided by either forced circulation or natural convection [12, 13]. Such efficient cooling is essential in maintaining the power transformer temperature below a specific thermal design requirement, primarily to adhere to an acceptable working life of the transformer [12, 13]. Apart from being a cooling agent, oil functions as an insulator. The oil insulates between components at different potentials, including the ability to withstand system transient due to lightning surges or switching [12, 14]. Oil significantly contributes to the efficiency of solid insulation by preventing spaces between layers of insulation, which could contribute to partial discharge [12]. Transformer oil also carries valuable diagnostic information about the condition of power transformers [11, 13, 14]. Due to the ease with which oil can be accessed with minimum interruption to power transformer operation, sampling and testing power transformer oil is a crucial prerequisite to subsequent transformer asset management actions [1].

1.2 Optical Fibre Sensor (OFS)

Optical fibre sensor (OFS) measures physical quantity based on its modulation on the intensity, spectrum, phase, and polarisation of light travelling through an optical fibre [15]. Small size, lightweight, multiplexing capabilities, chemical inertness, and immunity to electromagnetic fields are some of the widely known benefits of adopting OFS. These sensors often present high sensitivity, excellent linearity, and rapid response for real-time monitoring [16]. Studies on OFS, which have begun emerging in the 1960s [17], have undergone considerable expansion after decades of intensive research work. The principal reasons behind this substantial growth are their inherent ability to sense a variety of measurands [18], including refractive index (RI), strain, temperature, displacement, moisture, and pressure, to name a few. The OFS enables measurements of that variety of parameters in applications, where other sensor technologies fail or are simply unsuitable [19]. These main applications include biomedical and pharmaceutical applications [16, 20, 21], structural health monitoring [22, 23], chemical and biological sensing [24-26], as well as oil and gas exploration [27-30].

A diverse range of OFS have been reported in the literature, such as fibre grating sensors [31-33], fibre interferometer sensors [34, 35], fibre multimode interference (MMI) sensors [36-38], fibre surface plasmon resonance (SPR) sensors [39], microstructures fibre sensors [40], and Brillouin/Raman scattering [41], which have been significantly enhanced by embedding sophisticated technologies and advanced techniques. Those sensors use various types of specialty optical fibre, including few modes fibre [42], silica tube/rod [43], coreless fibre [44], multicore fibre [45], and photonic crystal fibre [46]. Most optical fibres are made primarily of silica. Silica has high mechanical strength, both tensile and flexural, as well as high flexibility and almost perfect elastic behaviour. Additionally, it is chemically stable and practically inert [18].

Fibre MMI sensor is a type of optical sensor that has been proven for its simple structure, yet high sensing performance. The basic structure to achieve an MMI device is a single-mode-multimode-single-mode (SMS) fibre structure, which is composed of a short segment of multimode fibre (MMF) sandwiched between two single mode fibres (SMFs). As for RI fibre sensors, an SMS constructed by an MMF is commonly insensitive to the change of surrounding RI due to the fact that guided modes are confined within the MMF and the surrounding RI does not alter the MMI. One common way to make the SMS-based sensor sensitive to the surrounding RI is to etch off the cladding of the MMF using hydrofluoric (HF) solution [47-49]. Nevertheless, a significant disadvantage of this technique is the difficulty of precisely controlling both the etched fibre diameter and the surface roughness [50]. As this technique can be easily affected by several environmental factors due to its high reliance on the etching solution concentration, temperature, and processing time [51]; fabricated sensors using etched MMFs have poor reproducibility. Similar to the role of cladding-etched MMF in the MMI sensor, a piece of silica rod (SR), which is made of 100% pure silica, also can be directly used to serve as the MMI section and the sensing head. When the surrounding RI is lower than the RI of SR, the sensing principle of the sensor is governed by modal interference in the SR. In the event where the surrounding RI is higher than that of the SR, the SR section becomes a leaky waveguide that supports continuous spectrum of radiation modes instead of normal guided modes [52], which could be useful in certain oil sensor designs.

1.3 Motivation and Problem Statement

The rapid advancement in technology coming about by the fourth industrial revolution (IR4.0) cannot be disregarded. The assembly of many technologies is needed for the implementation of this new industrial paradigm [53]. The role of sensors has increased substantially, mainly due to the emphasis of IR4.0 on interconnectivity, automation, and real-time data [54]. Real-time data refer to information obtained immediately after collection. It is one of the bases of IR4.0 [55] because failures are predicted based on real-time information received from sensors deployed in industrial applications.

Power transformer ageing evaluation based on oil testing is a simple concept that is analogous to human health check based on blood tests. The conventional techniques for transformer oil degradation control, such as breakdown voltage test and dissolved gas analysis (DGA), however, need special bulky equipment that demands frequent calibrations and high maintenance cost. These techniques require time-consuming testing procedures that consume lengthier time for the diagnostics of a power transformer. Therefore, such techniques cannot provide real-time diagnostics and this can lead to costly operational failure. In power transformer oil ageing detection, real-time data can be achieved by deploying a sensor with a remote or portable and simple interrogation system to enable in-situ measurement of the oil.

Optical fibre sensors (OFSs) are an excellent candidate for in-situ real-time detection of transformer oil degradation. Although many OFSs have been developed for the diagnostics of power transformers in recent years, only a handful of studies have focused on optical sensors for the detection of ageing transformer through oil RI. Notably, the RI of pure transformer oil exceeds the RI of silica fibre. As transformer continues to age, more ageing by-products, including acids and other particle contaminations are produced in the oil, which will eventually increase the RI of the oil on account of oil composition change [56]. Thus, the degraded transformer oil even has higher RI when compared to that of pure transformer oil [56]; signifying the need to bridge a huge research and knowledge gap in order to better understand and design new high RI sensors for detection of ageing transformer oil using optical fibres. Several studies have addressed the use of OFSs to measure high RI and ageing transformer oil using different techniques, such as Fabry-Perot interferometry (FPI) and lossy mode resonance (LMR) [57]. However, those sensors involve complex fabrications and their performances highly depend on additional coating materials. Besides, high RI sensing may be realised by exposing MMI structures directly in the field of measurement. Studies that employed this technique [52, 58-60] reported a common problem, where the cladding portion of the MMF demanded tedious chemical etching or the cladding removal process had exposed the core of the MMF to high RI environment. Such chemical corrosion makes the sensor become fragile and eventually can be omitted by directly employing SR to the sensor structure, thus minimising fabrication difficulties and improving safety margins. Additionally, fibre Bragg grating (FBG) [61, 62] and long-period grating (LPG) [63, 64] have also been used to detect ageing transformer oil. Despite the multiple existing techniques, none has executed sensitivity analysis or performance enhancement despite acknowledging that the key indicators commonly used to assess the performance of a sensor include, but are not limited to, sensor sensitivity, easiness of fabrication, temperature cross sensitivity, and sensor head size [65]. Hence, this present study proposes high RI sensors by incorporating SR structure after considering the aforementioned key performance parameters. For this purpose, four sensor designs based on MMI technique were designed. The sensitivity of the subsequent sensor was enhanced based on the sensitivity performance of the current sensor designs. The design that demonstrated adequate performance with the most suitable characteristics for in-situ measurement to obtain real-time information of the power transformer oil was deployed to transformer oil ageing detection application.

1.4 Research Objectives

Based on the research motivations and problem statements listed above, the research objectives of this study are listed in the following:

1. To develop new designs of high RI MMI fibre sensor based on silica rod.
2. To implement a systematic fabrication procedure using in-house facilities.
3. To evaluate the performance of the designed sensors through experimental work, subsequently verify their high RI sensing capability and potential real time application in detecting the degradation of transformer oil.

1.5 Scope of Study

This study focused on the development of high RI MMI fibre sensor for oil sensing based on SR and application in power transformer oil degradation detection. The development process began with conceptual sensor design, followed by sensor fabrication, sensor experimentation, and finally, sensor deployment to power transformer application. Each distinctive scope of this study is described as follows:

1.5.1 Conceptual sensor design

Initially, the development of the sensor design was guided by prior knowledge on light behaviour in optical fibre. BeamPROP software was used to numerically analyse the sensor structures in drawing form. The findings of the BeamPROP analysis, which included field distribution and sensor spectrum, gave initial assurance on the functionality of the sensor. The conceptual design of the sensor and its numerical simulation steps are described in detail in Sections 3.3 and 3.4, respectively.

1.5.2 Sensor fabrication

The fabrication of the sensor was carried out using in-house facilities. Each sensor design was brought into a real practical device through systematic fabrication procedure to enhance the quality and the reproducibility of the fabricated sensors. The sensor fabrication process is detailed in Section 3.5.

1.5.3 Sensor experimentation

The experimentation of the sensor was performed to determine the actual sensing capabilities of each proposed design. The experimental setup and characterisation procedure were the primary components of sensor experimentation. Similar setup was applied for each design since the measurands were the same. Meanwhile, the characterisation procedure was linked to the procedures executed to gather data. Sensor experimentation is elaborated in Section 3.6.

1.5.4 Sensor deployment to power transformer application

Sensor deployment to power transformer application was conducted to evaluate the actual performance of the sensor in detecting ageing transformer oil. The deployment mainly involved the establishment of remote experimental setup and procedure to enable in-situ real-time detection of ageing transformer oil, ageing process of transformer oil, and also characterisation procedure. Sensor deployment to power transformer oil application is described in Section 3.6.3.

1.6 Significance of Study

By exploring the importance of power transformer in power transmission and distribution systems, as well as the impact of power transformer failure on the community, there will be an expansion in understanding the need of real-time information on the condition of power transformer. The role of sensors is undeniably significant to achieve the above-mentioned need to ensure reliable electricity transmission. In this regard, this present study paves a path of power transformer ageing evaluation based on optical fibre, specifically SR, to detect transformer oil ageing. The approach of using optical fiber-based sensor not only leads to the advantages of simpler and convenient method without the need for any electronic equipment but also allows cost savings because it can eliminate the high cost of equipment maintenance and regular interval maintenance activities. Besides concentrating on the distinctive advantage of the use of OFS for the application, this study provides a detailed presentation on the development of the sensors and subsequently verified the capability of the developed sensors for an in-situ detection of ageing transformer oil to offer real-time information on the condition of the power transformer. The analysis presented in this study sheds valuable information for future research work in exploring the various sensor designs based on various types of optical fibre mainly for high RI or oil sensing.

Essentially, this study assessed the potential use of SR in oil sensing through oil RI monitoring. Since the RI range of the transformer oil exceeds the RI of SR, the developed sensors - so-called high RI fibre sensors – were initially tested with a series of high RI liquids ranging at 1.450-1.531. Four sensor designs based on SR structure are proposed in this thesis. The first design provides two ways of resolving RI responses from the output spectra and serves as the foundation to other designs. The second design poses a simpler structure and manages to simultaneously measure high RI and temperature. The third design achieves high RI sensitivity, ~ 5-fold and ~ 3-fold greater than the respective first and second designs but has cross sensitivity to temperature. Therefore, the temperature compensation for this design is attained by cascading the sensor structure to an MMF. Lastly, the fourth design that presents the simplest structure offers a full-intensity based RI sensor with adequately high RI sensitivity. This design demands no temperature compensation and can be applied with a single wavelength intensity-based setup for remote detection. Therefore, it is selected to be deployed in power transformer applications to detect degradation of power transformer oil.

1.7 Thesis Overview

This thesis presents the development of fibre RI sensors to detect ageing transformer oil. Four sensors were developed based on guided mode interference (GMI) and leaky mode interference (LMI) principles. In Chapter 1, the preliminary introduction of power transformer and OFSs are presented. Following that, motivation and problem statement of the study are discussed, with an emphasis on the current issues addressed by this research work. Based on the problem statement, the research objectives are outlined. The scopes of study and significance of this research work are explained in this chapter. Next, Chapter 2 introduces the comprehensive literature review on conventional techniques for transformer oil degradation control. The general overview of the type of optical fibre used in this work is included. In this chapter, theoretical background, such as the fundamental of GMI and LMI, is explained. A review of various available OFS configurations for detecting high RI and ageing transformer oil is presented. Comparison among sensor structures, techniques applied, and performance of the reported sensors is carried out and tabulated.

Chapter 3 discusses the methodology implemented for the main research components, including conceptual design, numerical simulation, fabrication, experiment setup, and experiment procedure. Chapter 4 reports the numerical simulation results for all sensor designs. The results comprise of field distribution for all sensor designs, sensor spectrum for Design 1 only, and analysis on different diameters of SR for specific sensor designs.

Results and analysis of the experimental work for Designs 1 to 4 sensors are reported in Chapter 5. For Design 1, the experimental results were analysed based on two aspects; wavelength and intensity, prior to the dip and the first peak of the sensor spectrum, respectively. For Design 2, a short section of SR sandwiched between two SMFs was cascaded to an FBG to achieve simultaneous measurement of high RI and temperature. A larger diameter of SR that exceeded the core and cladding of MMF was applied in Design 3 to achieve higher RI sensitivity. For this design, the sensitivity of the sensor was analysed based on the output power at the dip of the sensor spectrum. Design 4, which presents the simplest structure with remote setup, disregarded temperature compensation. It offers full intensity-based RI sensor with the highest suitability to detect ageing transformer oil. The ability of the sensor to detect the ageing of power transformer oil has been proven in this study. Lastly, Chapter 6 presents the conclusion, contributions, and some recommendations for future work endeavour.

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Appendix D

LIST OF PUBLICATIONS

Journal Papers

1. Saimon, S. M., Noor, M. Y. M, Azmi, A. I., Abdullah, A. S., Ibrahim, M. H., Salim, M. R., Ahmad, M. H., and Othman, A. F. (2022). Single-Mode-Multimode Silica Rod-Single-Mode High Refractive Index Fiber Sensor. *IEEE Sensors Journal.* (Q1, IF: 3.301)

2. Saimon, S. M., Noor, M. Y. M, Azmi, A. I., Abdullah, A. S., Ibrahim, M. H., Ahmad, M. H., Salim, M. R., Othman, A. F, and Alqazoun, F. A. H. (2022). A High Sensitivity Refractive Index Sensor Based on Leaky Mode Coupler of MMI. *IEEE Photonics Technology Letters*. 34(1): 63-66. (Q2, IF: 2.468)

3. Saimon, S. M., Noor, M. Y. M, Abdullah, A. S., Salim, M. R., Ibrahim, M. H., Azmi, A. I., Ngajikin, N. H., Ahmad, M. H., and Othman, A. F. (2021). Simultaneous Measurement of High Refractive Index and Temperature Based on SSRS-FBG. *IEEE Photonics Technology Letters*. 33(14): 715-718. (Q2, IF: 2.468)

4. Saimon, S. M., Ngajikin, N. H., Omar, M. S., Ibrahim, M. H., Noor, M. Y. M, Abdullah, A. S., and Salim, M. R. (2019). A Low-Cost Fiber Based Displacement Sensor for Industrial Applications. *Telkomnika (Telecommunication Computing Electronics and Control)*. 17(2): 555-560. (SCOPUS Indexed)

Proceedings Papers

1. Saimon, S. M., Noor, M. Y. M, Azmi, A. I, Abdullah, A. S., Salim, M. R., Ibrahim, M. H., Othman, A. F. (2022). High Refractive Index Fiber Sensing Based on Single-Mode-Silica Rod-Multimode-Single-Mode Fiber Structure. *Proceedings of Optical Communication, Devices and Sensors 2022.* 10-15.

2. Saimon, S. M., Noor, M. Y. M., Abdullah, A. S., Salim, M. R., Ibrahim, M. H., Othman, A. F., and Azmi, A. I. (2020). High Refractive Index Fiber Sensor Based on Silica Rod Structure. *Proceedings of the Lightwave Communication Research Group Colloquium 2020.* 43-46.

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